

**Produced water and hydrocarbon releases at the Osage-Skiatook petroleum  
environmental research sites, Osage County, Oklahoma:  
Introduction and geologic setting**

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**ABSTRACT**

The U. S. Geological Survey (USGS) is investigating the impacts of produced water and hydrocarbon releases at two research sites adjacent to Skiatook Lake in southeastern Osage County near Tulsa, Oklahoma. Site "A" is an area where produced water and hydrocarbon releases occurred primarily 65-90 years ago in an area of oak forest. The site is located in section 13, T22N, R10E near the neck of a small peninsula that extends into Lake Skiatook. The entire site is underlain by a surface layer of eolian sand and colluvium, and weathered and unweathered shale, mudstone, siltstone, clayey sandstone, and sandstone. Much of the site appears to have been impacted by early salt-water releases that killed the oak forest. The gently sloping upper part of the site is slightly eroded in places whereas the lower, steeper, more heavily salt-impacted portion has been eroded to depths of as much as 2 m (6.6 feet). The site has been mostly to partly revegetated with forbs and grasses. However, only a few oak trees have reestablished themselves. Oil from two redwood tanks at the south part of the site was transported via ditch to two roadside pits at mid-site. Oil spills from pipeline breaks and other tanks (no longer present) are scattered around the site. The oil in the west pit is highly weathered, but the east pit contains what appears to be relatively fresh asphaltic material.

Site "B" is located in section 29, T22N, R10E at the west end of a small bay of Lake Skiatook. The site includes an active production tank battery and adjacent large pit, two injection well sites, one with an adjacent small pit, and an old tank battery platform, all within 45 m (150 feet) of the lake. Hillslopes on the upper part of the site are characterized by a thin surface layer of eolian sand and sandstone clasts, underlain by weathered and unweathered shale. The lower terraced part of the site is underlain by a

surface layer of eolian sand and sandy to clayey colluvium and alluvium about 1.5 m (5 feet) thick and weathered and unweathered shale. Three salt scars extend downslope from the active tank battery, the injection well/pit, and the old tank battery platform to the lake edge. The area underlain by shallow saline ground water is substantially larger than the salt-scarred areas. Hydrocarbons can be detected in the shallow ground water adjacent to the active pit and at the lake edge below the pit.

## **INTRODUCTION**

In February 2001, the U. S. Geological Survey (USGS) initiated investigations of the impacts of produced water and hydrocarbon releases at two research sites adjacent to Skiatook Lake in southeastern Osage County near Tulsa, Oklahoma (figures 1, 2). These studies are designed to provide an in-depth understanding of the impacts of highly saline produced water and hydrocarbons on soils, vegetation, surface water and shallow ground water, and lacustrine fauna. These sites were chosen because of the similarity of the geologic and climatic setting of the sites to broad areas of the south-central U.S. oil-producing region, the presence of Federally owned lands and mineral rights under the jurisdiction of the Department of the Interior, and an adjacent public water supply and recreational fishery. Both sites are on land owned by the U.S. Army Corps of Engineers. The Osage Nation holds the mineral rights. Project results can be used to plan and evaluate cost-effective site remediation strategies, determine the rate of site restoration by natural processes, develop simple assessment techniques for other oil and gas production sites, and establish historic natural resource damage.

Both sites are in a dissected area of modest relief underlain by interbedded shale, mudstone, siltstone, and sandstone of the Pennsylvanian Wann Formation. Thick, resistant sandstone units typically form the hillcrests. Shale, mudstone, siltstone, and thin sandstone beds underlie hillslopes. Core drilling by the USGS indicates that the depth of weathering of the bedrock is about 10-25 m (33-80 feet) on the ridges and 5-6 m (16-20 feet) in small stream valleys.

These sites are located in the Cross Timbers ecosystem area of northeastern Oklahoma (1). Oak forests cover the hillslopes. The principal oak species are black jack oak (*Quercus marilandica*) and post oak (*Quercus stellata*). Grasslands and stands of oak occur on most ridge crests. Historically, this area has been used for grazing and hunting. Under natural conditions, fires control oak encroachment on grasslands.

In February and March of 2001, the sites were surveyed and mapped to characterize the local geology and cultural features. In February and March of 2002, both sites were drilled with a rotary rig, a hollow-stem auger rig, and a direct-push tool (Geoprobe<sup>1</sup>).

This paper provides the geographic and geologic framework for understanding and interpreting the results of the accompanying papers that follow.

### **“A” RESEARCH SITE**

The “A” site occurs in section 13, T22N, R10E at the neck of a small peninsula that extends into Skiatook Lake between the Cedar Creek arm of the lake to the east and the main stem (Hominy Creek) (figures 2, 3) to the southwest. The site is characterized a mostly open area within mature oak forest. Vegetation mapping (figure 4) shows that the site can be divided into two sections, one, north of the road, and the other, south of the road. The open area south of the road is vegetated by grasses, forbs, sumac, isolated oak, willow, and locust trees, and blackberry. A large sandstone outcrop area, devoid of vegetation except for lichen and mosses, lies in the southwest corner of the site. Remnants of two redwood oil tanks sit on sparsely vegetated sandstone outcrop in the southeast corner. Patchy weathered asphaltic oil covers an area surrounding the tanks. Several small oak trees grow within the area of weathered asphalt. A patch of immature oak trees occurs just north of the redwood tanks.

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<sup>1</sup> Use of a trade name does not constitute endorsement by the U.S. Geological Survey.

A narrow corridor of weathered asphalt extends from the area around the two tanks north to two unlined pits (A and B, figure 4). This feature follows an unlined trench (figure 5) that appears to have been designed to carry produced fluids from the two redwood tanks to the pits. This trench cuts across the natural topographic slope, which is northwest on this part of the site. The channel splits just upslope from the two pits with one branch leading to each pit. A badly corroded pipe exits pit A through its northern berm, and this pipe likely served to allow oil to be pumped from the pit into a tanker truck. The main channel changes direction about halfway between the tank area and the pit area and it appears that oil overtopped the channel at this point and spilled onto adjacent soils (figure 4). Pit A contains tarry or asphaltic hydrocarbon (figure 6) on which no vegetation grows. Oak trees lie to the east of the pit and a large, isolated oak tree grows just to the north of the pit berm (figure 6). Pit B is located to the west and shares a common berm with Pit A (figures 4, 7). This pit contains weathered asphalt. Sparse grasses grow on much of the surface. Water ponds at the low (north) end of the pit after rainfall. Two small, low areas occur west and southwest of the two pits (figure 4). During wet weather, the ground in these low areas is water saturated.

Hydrocarbons occur in soil northeast and southeast of the redwood tank area (figure 4). Both of these oil occurrences lie adjacent to repaired breaks in a pipeline passing the site and appear to be more recent than oil associated with the tanks, based on the degree of weathering. Weathered hydrocarbons also occur in a patch of soil about 6 x 6 meters (20 x 20 feet) just west of pit B.

In the southern part of the site near the two redwood tanks, the soil tends to be sandy because of the sandstone outcrop and subcrop. Weathered asphaltic oil fragments, mixed with sand, have washed downslope from the redwood tank area and the area of the eastern pipeline break forming areas of sandy outwash barren of vegetation contiguous with the initial spills.

This area south of the road drains in two divergent directions (figure 8). A drainage divide crosses this area from southeast to northwest such that most of the area

south of the road drains northwestward then westward off the site, eventually into a tributary arm of the main (Hominy Creek) stem of the lake. An area adjacent to the road that includes the two pits lies north of the drainage divide. Thus the surface area around the pits appears to drain mostly northward towards the Cedar Creek arm of the lake (figures 4, 8).

North of the road is an area of deeply eroded and disturbed soils (figures 4, 9). Sparse grasses grow except where the soil salt content is high. The deeply eroded section is largely delineated by a terrace edge (figure 4). Much of the section of disturbed soils (figure 4) is oriented approximately east-west across the south-central part of the area north of the road. Features on the 1937 aerial photo for the site suggest that this is the trace of an older road. The road was apparently moved southward as headward erosion of two gullies impinged on the roadbed. Three soil pedestals, in which the pre-erosion soil profile is preserved, occur within the deeply eroded section (see small, irregular hachured areas in figure 4; two pedestals are shown in figure 10). They are capped with grasses and forbs. A small oak tree grows on one pedestal. A small promontory on which two oak trees are growing extends into the deeply eroded section from the southwest. The area is drained by several washes that coalesce to the north before leaving the site. Flow occurs in these drainages only after rainfall, although it may persist for several days in the drainage at the north edge of the site (figures 4,10). Bedrock, including three outcrops of resistant sandstone ledges, is exposed in the deeply eroded section. A small wet soil area occupies the west corner of the deeply eroded section (figure 4).

Effluorescent salt crusts are observed at various times of the year. They commonly occur on the lower part of the central sandstone outcrop (figure 4, north central part of deeply eroded area) and on the surface of the alluvium along the channel below the central outcrop. Salts also are common around the soil pedestal in the south-central part of the deeply eroded area (figure 11).

### **Lease history (from files of the Bureau of Indian Affairs, Pawhuska, Oklahoma)**

Initial drilling on the lease was in late 1912 and 1913. Production is entirely from the Pennsylvanian Bartlesville Sand (local, informal name) at depths of 450-425 m (1475-1720 feet). Initial oil production for some of the 1913 wells was as much as 100 barrels/day (bbls/day). However, as of July 1, 1915, aggregate oil production for 8 wells was 46 bbls/day. The most recent drilling dates from 1976 and 1977 and was designed to retrieve oil from part of the lease that was due to be flooded when the Skiatook Lake was completed (as it was in 1984).

Most wells have been plugged and abandoned, some as early as 1913. Several well sites are presently under the waters of Skiatook Lake. All of these have been plugged and abandoned. However, many of these wells were plugged prior to the 1950s with “sand pumpings”, wood, lead, rock, “heavy mud”, and “blue shale”. These had to be replugged prior to flooding of the reservoir because these materials tend to fail. The usual reason for plugging and abandoning was low production. One well, plugged in 1931, was producing 2 gallons of oil and 25 bbls of water/day. Another, plugged the same year, was producing 1.5 bbls of oil and 20 bbls water/day.

Production through 1981 was about 100,000 bbls of oil. Anecdotal reports indicate that the lease produced substantial quantities of gas that was used locally to power pumping units (Marvin Abbott, USGS, 2001, oral communication). As of 2002, one well on the lease still had a gas-fired pump. Records do not indicate that the lease was ever considered for waterflooding. At least one production well was converted to a salt-water disposal well. One initial production report notes that the oil was 35° API gravity

## **Geology of the “A” site**

The site is typically underlain by 1) a surface layer of modern eolian sand or mixed eolian and slopewash sand of varying thickness (0 cm to 1 m; 0-3.3 feet); 2) sandy or clayey colluvium that ranges from a thin layer of granule-pebble weathered sandstone-clast conglomerate to large boulders of sandstone; 3) weathered shale, mudstone, siltstone, clayey sandstone, and sandstone; and 4) similar underlying unweathered bedrock. The eolian sand, colluvium, and the uppermost part of the weathered bedrock are exposed in the deeply eroded area and were also observed in several Geoprobe holes at the site. A more complete section of weathered bedrock down to and penetrating into unweathered bedrock was observed in auger holes.

### **Bedrock geology**

#### **Lithology**

The bedrock units (figures 12, 13) mapped at the surface at the “A” site are part of the Pennsylvanian Wann Formation (2). The sandstone in the uppermost part of the site near the redwood tanks (figures 12,13) is herein mapped as the lower part of the Clem Creek Sandstone Tongue of the Wann Formation whereas the underlying rocks which are locally exposed in the lower part of the site belong to the lower shale member which here is comprised of beds of shale, siltstone, clayey sandstone, sandstone, and mudstone.

The lowermost part of the Clem Creek sand forms the sandstone outcrop in the southwest corner of the open area (figure 12). Patches of sandstone interspersed with thin sandy soil occur around the two redwood tanks showing that the Clem Creek sand also underlies the tanks. The contact between the Clem Creek tongue and the underlying sequence is not exposed on the site, but can be recognized by a gentle break in slope at the low, north edge of laterally discontinuous exposures of nearby sandstone.

Bedrock is not exposed between outcrop of the Clem Creek Sandstone Tongue near and southwest of the redwood tanks and the road that traverses the site. Shallow auger holes south of the road (AE05, 06, 07, figure 12) show that the bedrock in this area

is comprised mostly of clayey sandstone, with lesser sandy shale and siltstone. A single large sandstone boulder occurs in the gently eroded area west of the pits (“B”, figure 12). It is unclear whether this is a colluvial boulder derived from sandstone outcrops upslope or outcrop of an underlying resistant sandstone layer within the bedrock.

North of the road, in the deeply eroded area, clayey sandstone, mudstone, shale, siltstone, and sandstone crop out. All units are weathered and most units form poor exposures except in some of the deeper gullies. Resistant sandstone ledges crop out in three areas: the west edge, the center, and the north part of the deeply eroded area (figure 12). The outcrop at the west edge consists of cross-bedded sandstone. The weathered surface is mottled grayish orange, yellow gray, and olive gray<sup>1</sup>. Small surface pits weather moderate yellow brown.

The resistant sandstone outcrop in the center is exposed in a deep gully where it is underlain by less resistant clayey sandstone and sandy mudstone. It consists of thickly bedded sandstone. Small pits pockmark most exposed sandstone surfaces. Pits up to about 10 cm across have formed locally in the weathered surface. Broken surfaces are very light gray to light gray in color whereas the weathered surfaces are typically mottled very light gray and dark yellow orange to moderate yellow brown, occasionally moderate red to gray red. The small pits coincide with vertical burrows whose cross-sections can be seen on some weathered surfaces or on freshly broken rock.

The sandstone outcrop to the north consists of thickly bedded sandstone, which is very light gray to light gray on freshly broken surfaces. It weathers dark yellow orange to moderate yellow brown, occasionally moderate red to gray red. This outcrop is weakly pitted in exposures near the lake and at the south end of the outcrop. Except for the intervening patch of overlying colluvium and eolian sand, this outcrop would be continuous with the sandstone in the center.

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<sup>1</sup> Colors used here and elsewhere are derived from the “Rock Color Chart” published by the Geological Society of America.

To the southeast of the deeply eroded area is an arcuate zone of large flat slabs of sandstone up to 3.6 m (12 feet) across mapped as part of the colluvium (ENE-trending, light reddish brown area marked by a string of “B”s in figure 12). These sandstone slabs dip gently downslope along the length of the exposure. Many are contiguous, but in some places gaps occur between slabs. These sandstone slabs are interpreted as large pieces of a well-indurated bed that have weathered from the outcrop, have been undercut by erosion of the less-resistant underlying sediment, and have moved downslope. If so, the sandstone bed from which these slabs are derived may lie beneath the overlying surficial cover a few meters (several feet) upslope. It appears that this sandstone bed does not extend westward across the width of the research site as no sandstone ledge is exposed along strike in the deeply eroded area where gullies extend southward towards the edge of the road (figure 12).

The bedrock units exposed at the surface in the deeply eroded area persist in the subsurface and were observed in Geoprobe and auger holes as portrayed in Figures 14 and 15. Figure 14 is an east-west cross section along the road through augerholes AA04, AA02, and AA03. These three augerholes intercepted sandstone, clayey sandstone, mudstone, and shale. Some thin coaly beds were intercepted in AA04. The sections are dissimilar enough between the three holes that no correlation from one hole to the next seems reasonable. Unweathered bedrock was intercepted in AA02 and AA04 at depths of 14.4 m and 4.6 m, respectively. AA03 did not penetrate unweathered bedrock.

Figure 15 is a north-south cross section that extends from the sandstone outcrop area north to a point close to the lake. All holes south of the road are shallow. Thus, bedrock information is limited in that part of the cross section.

## Structure

The sedimentary section on the peninsula is everywhere very gently dipping, and the regional dip is on the order of 1-2° to the west (2). Locally in the Skiatook Lake area, however, the section is faulted and gently folded. Small domal structures occur in the section that are often the locus of oil accumulation in the subsurface.

The sandstone bedrock ledge in the northern part of the deeply eroded area extends southwest to the outcrop in the center of the deeply eroded area, interrupted only in one area by overlying uneroded colluvium and eolian sand. Along its extent, the upper contact appears to rise in altitude from about –35 feet (–10.7 m) with respect to datum to about –29 feet (–8.8 m) with respect to datum (figures 8, 12). If so, this information suggests a local southeasterly dip for this sandstone bed, although the strike and dip are not measurable without at least one additional reference point because the outcrop is so linear. In the central sandstone outcrop, one bedding surface in the lower part of the exposure shows a series of filled fractures, the most prominent of which are oriented 040°, approximately parallel to the trend of the sandstone outcrop. These fractures may be related to a local structural feature, such as a small fault or the crest of a small anticline or both. The transition from weathered bedrock to unweathered bedrock in both AA04 and AA02 takes place where the section is changing from dominantly sandstone to dominantly shale (figure 14). This transition is offset about 10 m vertically between the two holes. A fault may be inferred between AA04 and AA02. The apparent dip on the sandstone beds at the surface in the deeply eroded area may represent drag on a normal fault

Specific structural interpretations cannot yet be drawn from the exposures in the deeply eroded area or from the drillhole data and mapping of the rest of section 13 may have to be completed to determine whether faults or small folds are present.

### **Surficial geology**

The surficial deposits consist of colluvium, eolian sand, and mixed eolian sand and sandy slopewash. These units are exposed in the deeply eroded area north of the road and in the more gently eroded areas west and southwest of the two pits south of the road (figure 12). The colluvium ranges from a thin layer of weathered granule-pebble sandstone-clast conglomerate to large boulders of sandstone within a sandy matrix. The weathered granule-pebble sandstone-clast conglomerate is the most widespread facies, occurring in the gently eroded areas west of the pits and around most of the margin of the deeply eroded area. These granule to pebble beds blanket parts of the deeply eroded area

forming small terraces (figures 8, 12) adjacent to some of the stream channels. The granule to pebble colluvium and overlying eolian sand are well exposed in the soil pedestal in the north-central part of the deeply eroded area (figure 16). Locally, a clayey colluvial facies is present. This facies consists of isolated sandstone clasts in a clayey matrix comprised of weathered shale. It appears to consistently underlie the sandy granule-pebble colluvium, but additional exposures need to be documented to confirm that relationship.

The boulder beds in the colluvium occur downslope from outcrop or subcrop of resistant sandstone beds on the northwest and northeast sides of the deeply eroded area (marked by “B” in the northern part of figure 12). The boulders that occur about 10-15 m north-northeast of the sandstone outcrop at the west edge of the deeply eroded area (figure 12) are identical in appearance (presence of crossbeds, color and weathering characteristics) to the sandstone in the outcrop and thus are inferred to have been derived from it. A train of sandstone cobbles and boulders is also exposed in the small scarp along the northeast edge of the deeply eroded area. These boulders resemble the sandstone slabs found to the southeast (discussed above) and may be derived from that outcrop/subcrop area.

Throughout the central and northern parts of the site, eolian sand forms a discrete layer that mantles the underlying colluvium and is widely exposed at the surface in areas around and within the deeply eroded area (figures 12, 14, 15, 16). It is composed of very well sorted, fine to very fine sand grains. Thin pebbly layers and isolated sandstone pebbles occur within the lower part of the eolian sand suggesting that the eolian sand has been locally reworked by slopewash, since the sandstone pebbles are derived from upslope exposures of weathered bedrock. An A soil horizon, characterized by stained fine sand, is developed in the upper part of the eolian sand layer (figure 16). In the south part of the site, the eolian sand appears to be mixed with sand derived from weathering of the sandstone bedrock exposed there.

## **Hydrology**

During wet periods such as early March 2001, water flows across the surface in small drainage ways and water-saturated ground occurs at the surface at several localities within the research site. Most of the drainage ways and saturated localities are marked in blue or with a marsh symbol on figures 4 and 12. Present, but not mapped in figure 12, is modern alluvium that occupies the valley floor under the main channel for a few tens of meters upvalley from the lake. Based on the observed textures of the units exposed in the deeply eroded area and the location of wet places, it seems likely that the colluvium and the eolian sand are the most permeable units on the site. Among the bedrock units, it seems likely that the sandstone beds are the most permeable. Following rainfall, water seeps from the sandstone outcrop in the center of the deeply eroded area days after the rest of the site has dried up (figure 10). Ephemeral salt crusts form on the lower parts of the sandstone outcrop and on the surface of the alluvium as drying occurs.

### **“B” RESEARCH SITE**

The “B” site occurs in the southeast corner of 28, T22N, R11E in southeastern Osage County about 5.3 km (3.3 miles) southeast of the “A” site. It consists of a mostly open area on a hillslope and terrace at the west end of a small bay off the main part of Skiatook Lake (figures 2, 17, 18). Two small streams feed into the bay to the north and south of the research site. The open area is surrounded by mature oak forest that covers the adjacent hillslopes. Access roads cross the site and traces of an older roadbed marked by limestone gravel occur in the central part of the site. The open area is occupied mainly by grasses and forbs, cut and fill, pits, salt scars and a few isolated oak trees and a few small groves of oaks (figure 18).

At least three tank batteries have been constructed at this site. An active tank battery and adjacent pit about 26 m across occur in the south part of the site. A salt scar extends from the east edge of the pit berm down to the lake (figure 18, 19). An old tank battery site, presently (2002) marked by a flat graded area with some piles of rubble,

occurs in the central part of the site. A second salt scar extends down to the lake from the east edge of this graded area. Two tanks were removed in 1999. A tank, injection well, and pit about 10 m across occur in the north part of the site and a third salt scar extends downslope towards the lake from the east edge of the pit berm. This salt scar terminates in a shallow pit separated from the lake by a low berm. An additional injection well occurs on the northeast part of the site across the north creek (figure 18).

Oil-saturated soils occur on the hillslope to the west of the southern tank battery. They are associated with breaks in two pipelines (unmapped) that traverse the upper part of the site. Another area of oil-saturated soil occurs just east of the pit adjacent to the southern tank battery. The 1960 aerial photo suggests that a tank that predates the present pit was located at this site. Three small areas of oil-saturated soils are located near the stream in the northern part of the site. They are also near old pipeline breaks.

The salt scars below the 3 tank batteries were remediated in the fall of 1999 by removing 15 cm (6 inches) of salty surface soil, replacing it with clean soil, covering the areas with straw, and seeding with winter wheat (G. Berschue, U.S. Army Corps of Engineers, 2001, oral commun.). Salt crusts are common on the remediated areas and have also been observed in a barren patch of saline ground near the lake's edge (figure 18). Growth of planted grasses was reasonably successful the first growing season (2000), but most of the grasses have since died, especially below the active pit.

The entire site slopes generally eastward towards the lake or the small creek (figure 20). The lower parts of the site adjacent to the lake and north stream form a gently sloped terraced area. During lowstands of the reservoir, it is apparent that the north and south stream channels are incised below the level of this terrace

#### **Lease history (from files of the Bureau of Indian Affairs, Pawhuska, Oklahoma)**

This lease was initially drilled in 1938. Production began in 1939. The initial target was the Bartlesville Sand (local name). The productive unit proved to be the

Cleveland Sand (local name). The Cleveland Sand occurs at depths of 260-305 m (850-1000 feet) below the surface. Oil is localized by a small, northeast-trending dome with about 10 m (35 feet) of structural relief. The initial production was solution-gas driven. Waterflooding was initially investigated in 1948 and began in late 1951 when a single salt-water disposal well was drilled into the productive unit and used to test the potential for waterflooding. A full-fledged waterflood was proposed in March 1953 and began shortly thereafter. In January 1953, there were 10 producing wells on the lease averaging 21 bbls/day total oil production. Through January 1953 the lease had produced a little less than 110,000 bbls of oil. Production continues today at approximately 10 bbls/day for the lease (S. Hall, lease operator, oral commun., 2002).

### **Geology of the “B” site**

The entire site is underlain by bedrock composed of 1) near-surface weathered shale, and minor siltstone and sandstone and 2) similar underlying unweathered bedrock. Eolian sand and sandstone-clast colluvium of varying thickness cover bedrock on the hillslopes and thicker eolian sand, colluvium, and alluvium cover bedrock in the terraced area adjacent to the lake (figure 21).

### **Bedrock geology**

#### **Lithology**

The bedrock units mapped at the surface at the “B” research site are part of the Pennsylvanian Wann Formation (2). The lower shale member of the Wann underlies the entire area of Figure 21. Thick sandstone beds of the Clem Creek Sandstone Tongue crop out upslope west of the map area and are the likely source of many of the sandstone clasts that occur in the colluvium and alluvium at the site.

The shale is well exposed in the road cut on the hillslope west of the northern tank and injection well. The upper 0.5 meters of the shale weathers moderate red orange to moderate red brown and grades downward to weathered shale that is light olive gray, yellow gray, and, locally, very dark yellow orange in color.

Two to three thin sandstone beds, in aggregate probably less than 1 meter thick, occur in the site area. They crop out in the bottom of the north streambed just upstream from the lake (figure 21). From there to the east, their trace is covered by alluvium and fill, but beyond the fill area the sandstones can be observed as large blocks of sandstone float along the steep hillslope at the edge of the lake. Similar sandstone crops out on the west side of the active pit. This sandstone can be traced southward into trees south of the site area. It is uncertain whether the sandstone beds in the stream bottom are the same as the sandstone beds exposed in the pit.

In all outcrop and float areas, the sandstone is very fine-grained, light olive gray on fresh surfaces, and weathers moderate yellow brown, dark yellow brown, dark yellow orange, and moderate red orange. It is well cemented and has very well-developed joints spaced 10-50 cm (4-20 inches) apart that cause the sandstone to break up into slabs 12-20 cm (5-8 inches) thick and as much as 1.8 m (6 feet) long.

The shale and thin sandstone beds were encountered in three augerholes (BA01, 02, and 03, figure 21) and in the lowermost part of several Geoprobe holes (figure 21). The bedrock geology observed in these holes is portrayed in Figures 22 and 23. The thin sandstones observed in the west wall of the active pit can be correlated with sandstones at depth in augerhole BA02 (figure 22). In all three augerholes, several very thin sandstones 2-5 cm (1-2 inches) thick were observed, some of them water bearing. The thickness of weathered bedrock ranges from 3-5.5 m (10-18 feet). The sandstones and shales in unweathered bedrock are varying shades of gray. Thin concretionary beds typically less than 1 cm (0.4 inches) thick are common in the shale.

Exposed sandstone beds on the bluffs around the site dip gently westward, although exposures within the site are insufficient to establish the local dip.

## **Surficial geology**

The surficial deposits overlying the shale and sandstone consist of colluvium, eolian sand, and alluvium (along the creek to the north). On the steep hillslopes west of the three tank battery sites (figure 21), the colluvium is relatively thin and does not form a discrete layer, but rather colluvial material occurs as scattered granules, pebbles, cobbles, and boulders of sandstone within a matrix of clayey eolian sand. These sandstone clasts sometimes rest directly on the underlying weathered bedrock and sometimes lie within or on the surface of the sandy layer.

Colluvium is much thicker (1 m, 3.3 feet, or more) on the steep southeast-facing hillslope northeast of the north creek adjacent to the injection well pad. Angular granules, pebbles, cobbles and boulders of sandstone in a sandy matrix are exposed in the road cut at the edge of the cut and fill area surrounding the injection well north of the creek (figure 21).

Low on the hillslopes below the tank batteries is a break-in-slope (figure 20) below which is a terrace underlain by a thicker section of colluvium and overlying eolian sand. This section averages 1.5-1.8 m (5-6 feet) thick (figure 23). The colluvium varies from pebbles, cobbles and boulders of sandstone in a matrix of clayey to silty sand to clayey, shale-clast colluvium with only scattered sandstone clasts. The sandstone clasts in the sandy facies are usually friable and often have a thick oxidation rind.

The eolian sand layer overlying this colluvium is comprised of very fine-grained sand to clayey and silty very fine grained sand as much as 55 cm (22 inches) thick. The sand is very well sorted. A dark yellow brown soil horizon has formed in the upper part of it. The lower part of the eolian sand layer is dark yellow orange in color and includes granules and small pebbles of weathered sandstone suggesting some reworking of the sand, probably by slope wash. This layer erodes readily and has been stripped from much of the site (figure 21), probably by erosion that followed road building and erosion after salt-water saturation of the soil below the tank batteries.

The alluvium along the creek is composed of sand and gravel with abundant large cobbles and boulders of sandstone. At least one terrace occurs within the mapped alluvium. Near the lake, the creek has cut down to sandstone bedrock (figure 21) and a stream-cut terrace edge about 0.75 m (2.5 feet) high composed of 0.45 m (1.5 feet) of weathered shale and 0.3 m (1 foot) of overlying colluvium is exposed.

During lowstands of the reservoir (see below), lake bottom sediments are exposed (figure 21). Areas of gravel and boulders, sand, and lake bottom silt and clay occur. The gravel, boulders, and sand represent sediment reworked from the alluvium and colluvium by wave action. Abundant leaf litter is mixed with the lake bottom silt and clay.

## **Hydrology**

The stream at the northern edge of the site drains a small basin to the northwest and feeds into the waters of the cove. A second stream occurs south of the site (see figure 17) and drains another small basin. Surface hydrology within the site has been altered substantially by the roads, cut and fill areas, pits, and erosion channels that originate in disturbed areas upslope from the site. Water tends to follow these artificial drainageways. Water ponds in a small ditch along the dirt road northeast of the north tank battery during wet periods.

The relatively thick section of colluvium and alluvium beneath the terrace represents a major pathway for subsurface movement of produced water releases from the pit towards the lake.

The elevation of the lake surface varies in response to water input, evaporation and other losses, and releases by the U.S. Army Corps of Engineers. The normal pool elevation is 218 m (714 feet) above sea level. During the course of this study the pool elevation has varied from a little over normal pool (figure 19) to as low as 215.5 m (707 feet). The lake surface elevation has an impact on the local hydrology in that it affects the local base level for ground water and surface water flow. Areas of ground water seeps are exposed under lowstand conditions.

## CONCLUSIONS

Research sites “A” and “B” on Lake Skiatook provide excellent opportunities to study the impacts of produced water and hydrocarbon releases on soils, surface water, ground water, and the ecosystems they support. Site “A” is the older site where production activities ceased perhaps 65-70 years ago and the site has been partly reclaimed by natural processes. A salt scar persists on the lower part of the site north of the road and erosion continues. The upper part of the site has limited initial and continuing erosion although weathered asphalt mixed with sand is eroding from oil spill areas near the two tanks and moving downslope. These areas are devoid of vegetation. Pit “A”, with relatively fresh-appearing asphalt, is devoid of vegetation in the main part of the pit, but some grasses are starting to colonize the upper margin. Pit “B” has a greater level of colonization by grasses although the north end of the pit, which frequently has ponded water, remains devoid of vegetation. Tree-ring chronology and geochemical studies of oak trees within and adjacent to the open area may lead to a better understanding of the site history and impacts.

Movement of fluids in the subsurface of site “A” is likely to occur primarily in the relatively thin colluvium and overlying eolian sand. The persistence of vegetated pedestals within the deeply eroded area, even one pedestal that weeps salts, suggests that the salts can bypass the root zone of plants where the eolian sand and colluvium are thick enough. The upper part of the weathered bedrock may be storing and slowly releasing salt accumulated while an active source was present. The sandstone outcrop in the middle of the deeply eroded area continues to weep substantial amounts of salt suggesting that this sandstone may be a significant pathway for saline fluids in the weathered bedrock.

The two pits are an apparent source of salt for the deeply eroded area. Two gullies are eroding headward towards the position of these two pits (figure 21). Headward erosion in other directions suggests that other sources of salt may have

originally been present at site “A”, but the direct evidence is now missing. The variable pitting and mottled very light gray to red, orange, and brown colors observed in the sandstone outcrops at this site are typical of salt-damaged sandstone observed by the authors at oil production sites throughout eastern Osage County.

Site “B” has recent releases of produced water and hydrocarbon. This site provides an opportunity to evaluate the transport of produced water salts and hydrocarbons to Lake Skiatook. Aside from the physical impacts of road construction and site preparation through cut and fill, the salt scars below the three tank battery sites are the most visible impacts, although substantial erosion of the surface soil layer from much of the terrace area has occurred between the three salt scars. Isolated low soil pedestals are found within this terrace area suggesting that parts of the terrace were isolated from the causes of erosion (roads or shallow saline groundwater).

The colluvium and alluvium beneath the terrace area is a likely pathway for transport of produced water. The amount of clay in the colluvium varies across the site suggesting that sandy colluvial facies are likely to have higher permeability and be a preferred pathway. The upper part of the weathered shale bedrock may store salts to some degree, but the shale would seem to be a barrier to downward movement of contaminants except where fracture permeability is significant. The thin sands and the concretionary beds may offer some pathways for fluid movement especially where they are fractured.

A grove of small oak trees grows adjacent to the edge of the active pit berm. These trees are apparently hydrologically isolated from salt and hydrocarbon releases from the pit. Study and monitoring of these trees may lead to further insights regarding history and ecosystem impacts at this site.

#### **REFERENCES CITED**

- 1 Kuchler, A.W., 1964. Potential natural vegetation of the conterminous United States (map and manual): Amer. Geogr. Soc. Spec. Publ. 36

- 2 Gardner, William E., Geology of the Barnsdall area, Osage County, Oklahoma:  
Master's thesis, The University of Oklahoma, Norman, Oklahoma (1957)



Figure 1- Location map for the Skiatook Lake area in southeastern Osage County.

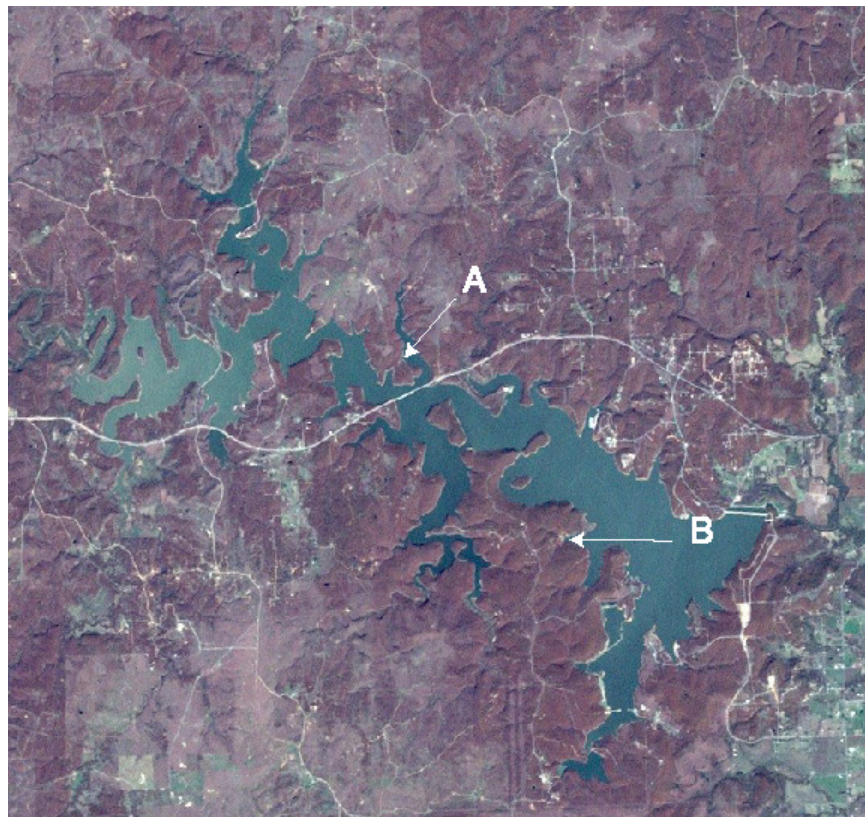


Figure 2- 1999 Landsat image of the Lake Skiatook area showing the location of research sites A and B. State Highway 20 traverses east-west across the middle of the image.

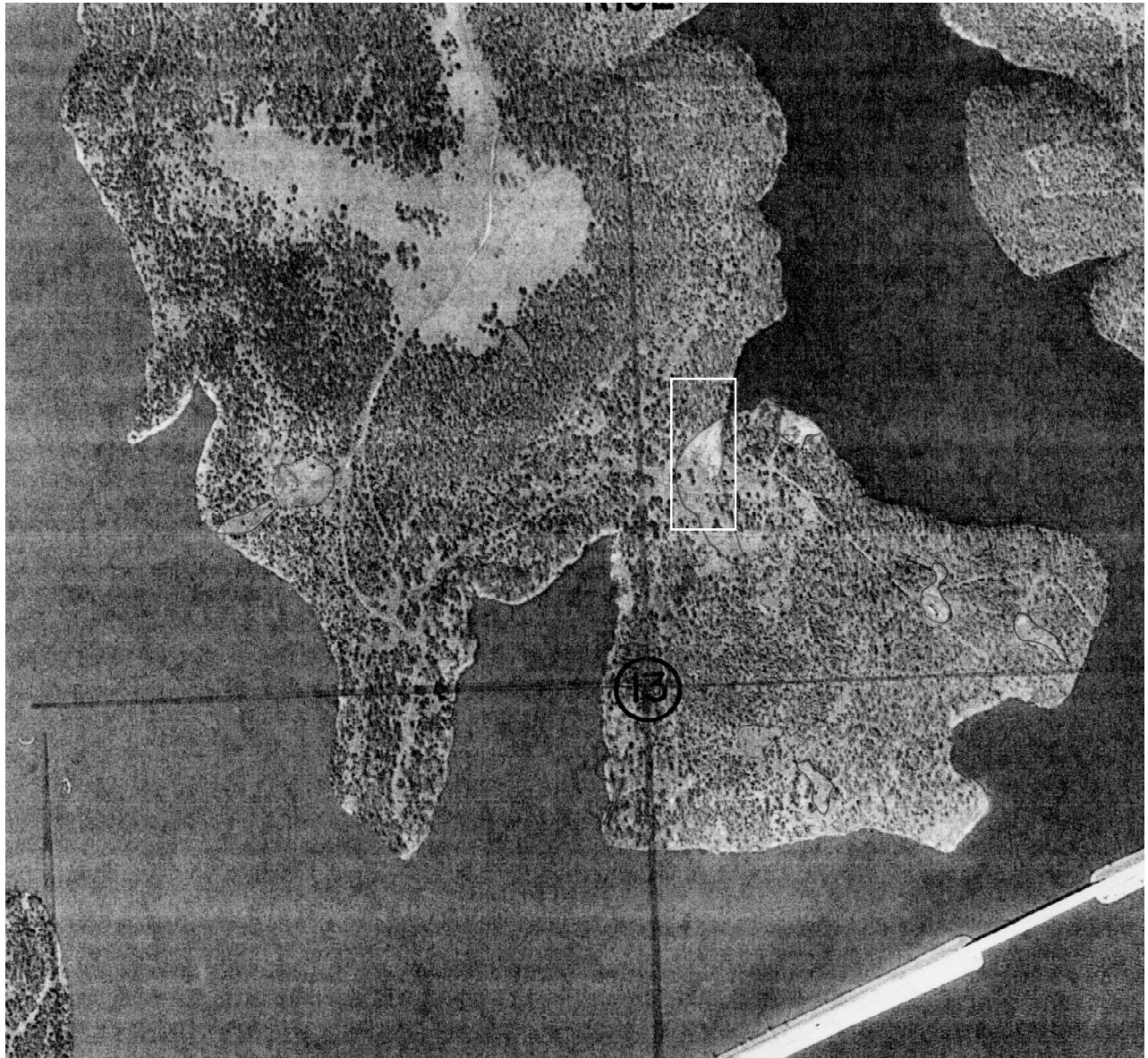


Figure 3- 1995 aerial photo of part of section 13 showing the location of the “A” research site (outlined in white, about 140 x 230 m, 450 x 750 feet) adjacent to Skiatook Lake. Note the Highway 20 bridge at lower right.

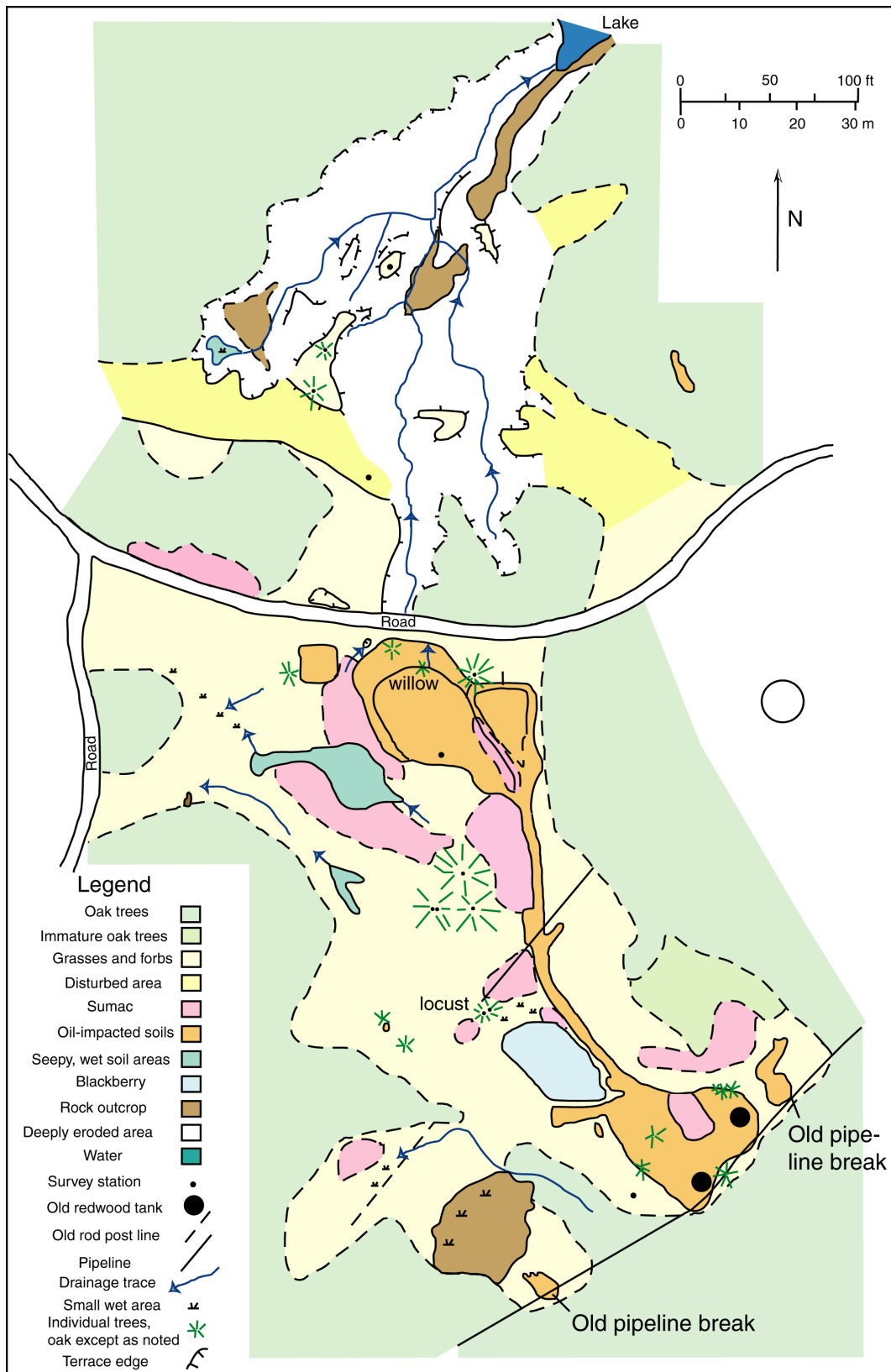


Figure 4- Vegetation map of the "A" site.



Figure 5- Trench with weathered asphalt between redwood tanks and pits (looking south upslope towards the location of the tanks). Note the sumac with one or two small oaks to the right and the mature oak forest in the background.



Figure 6- Pit "A" with asphaltic hydrocarbons.



Figure 7- Pit “B” with highly weathered hydrocarbons and sparse grasses. The photographer is standing on the berm between the two pits. The north edge of the pit berm is to the upper right. A willow tree grows just beyond this berm (see Figure 4), sumac is growing beyond the pit to the left.

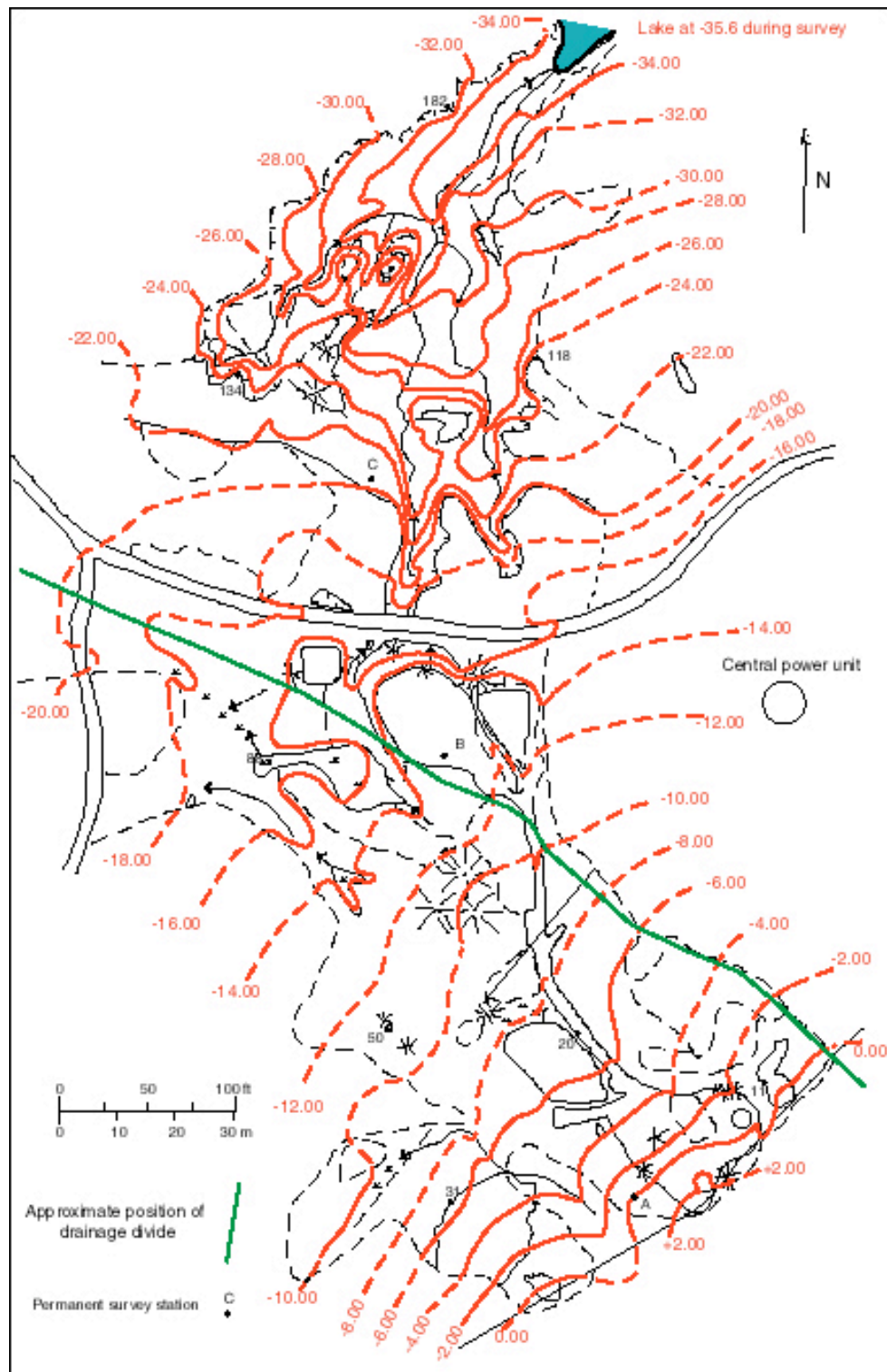


Figure 8- Topographic map of the "A" site showing the drainage divide.



Figure 9- The deeply eroded area, August 2000, from near the road looking north.



Figure 10- Surface flow disappearing below the surface of the stream alluvium within the deeply eroded area, March 10, 2001. Two soil pedestals are delineated by arrows (right and left). Sandstone bedrock outcrop is delineated by a rectangle.



Figure 11- Salt effluoresence adjacent to soil pedestal.

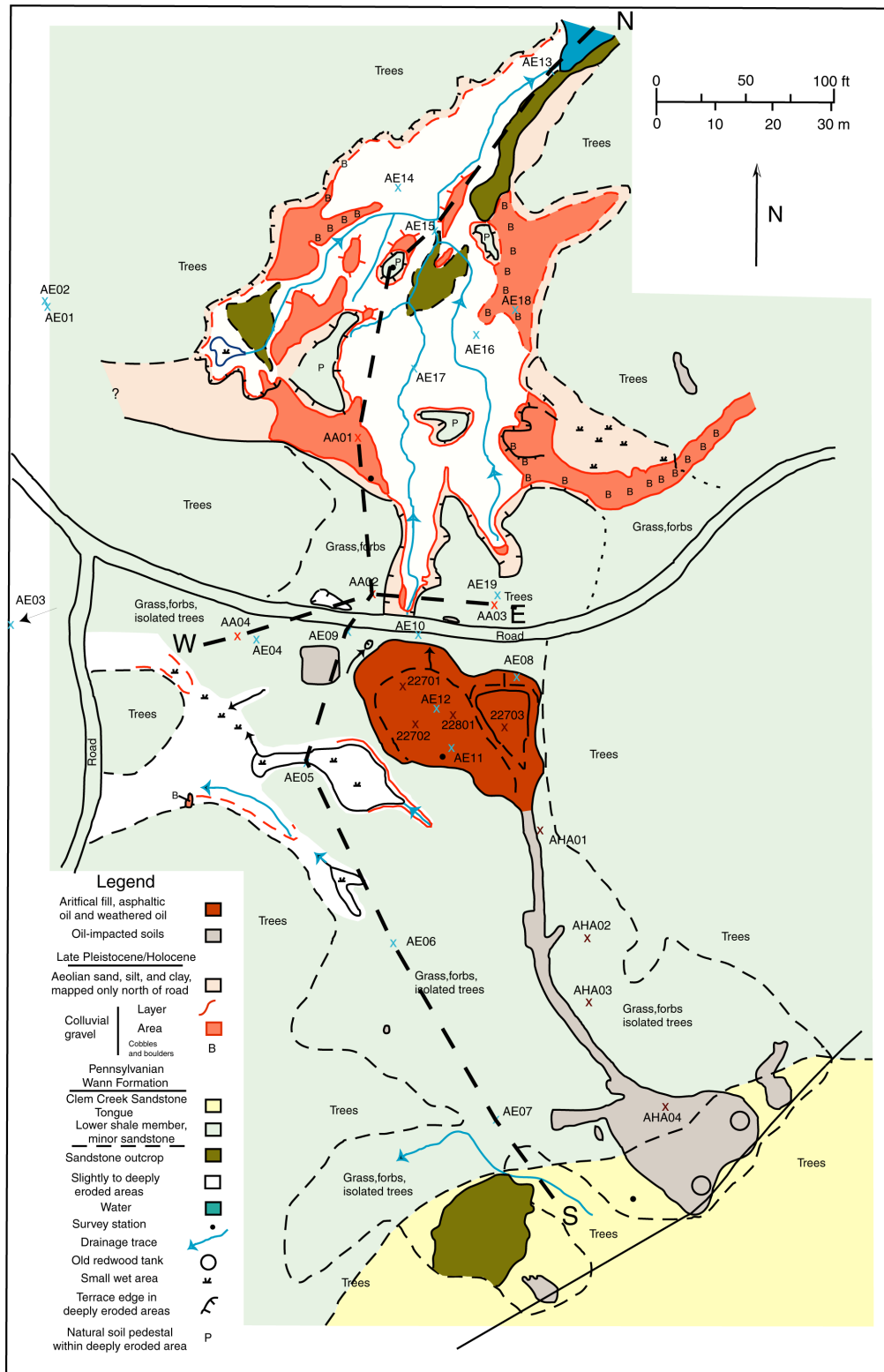


Figure 12- Geology of the “A” site showing locations of drillholes and cross sections.

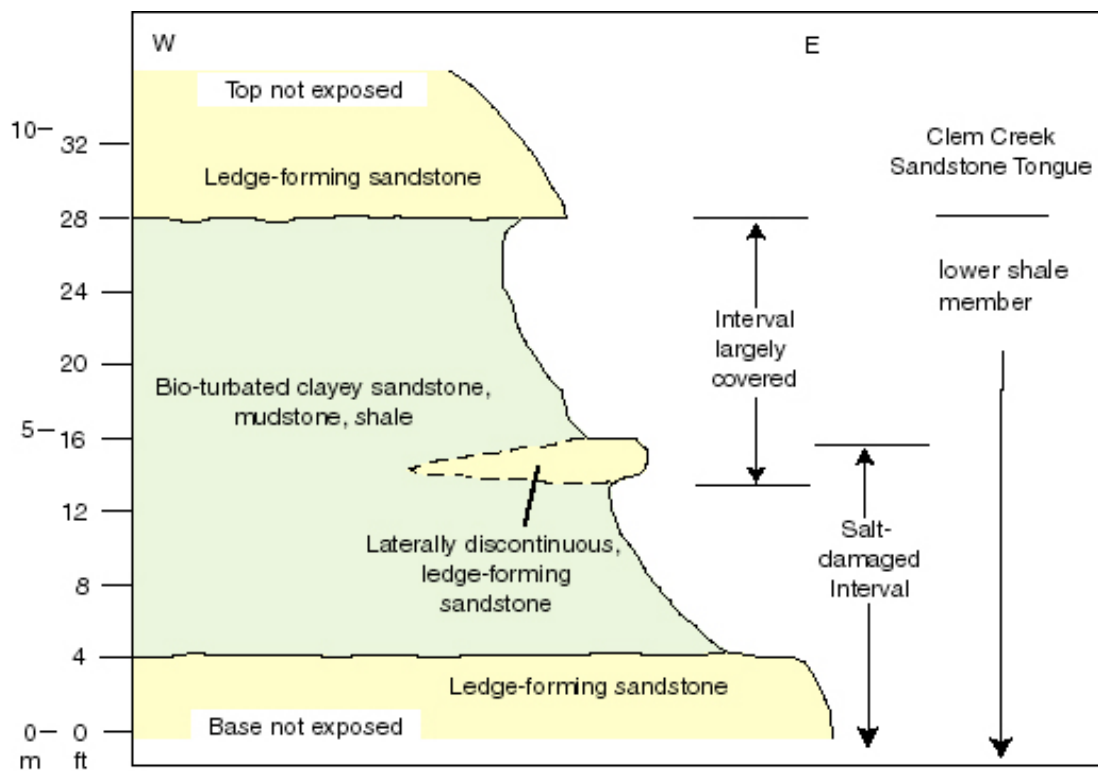


Figure 13- Generalized bedrock section at “A” research site. Thicknesses are estimated from contour map. Section is part of the Pennsylvanian Wann Formation (2).

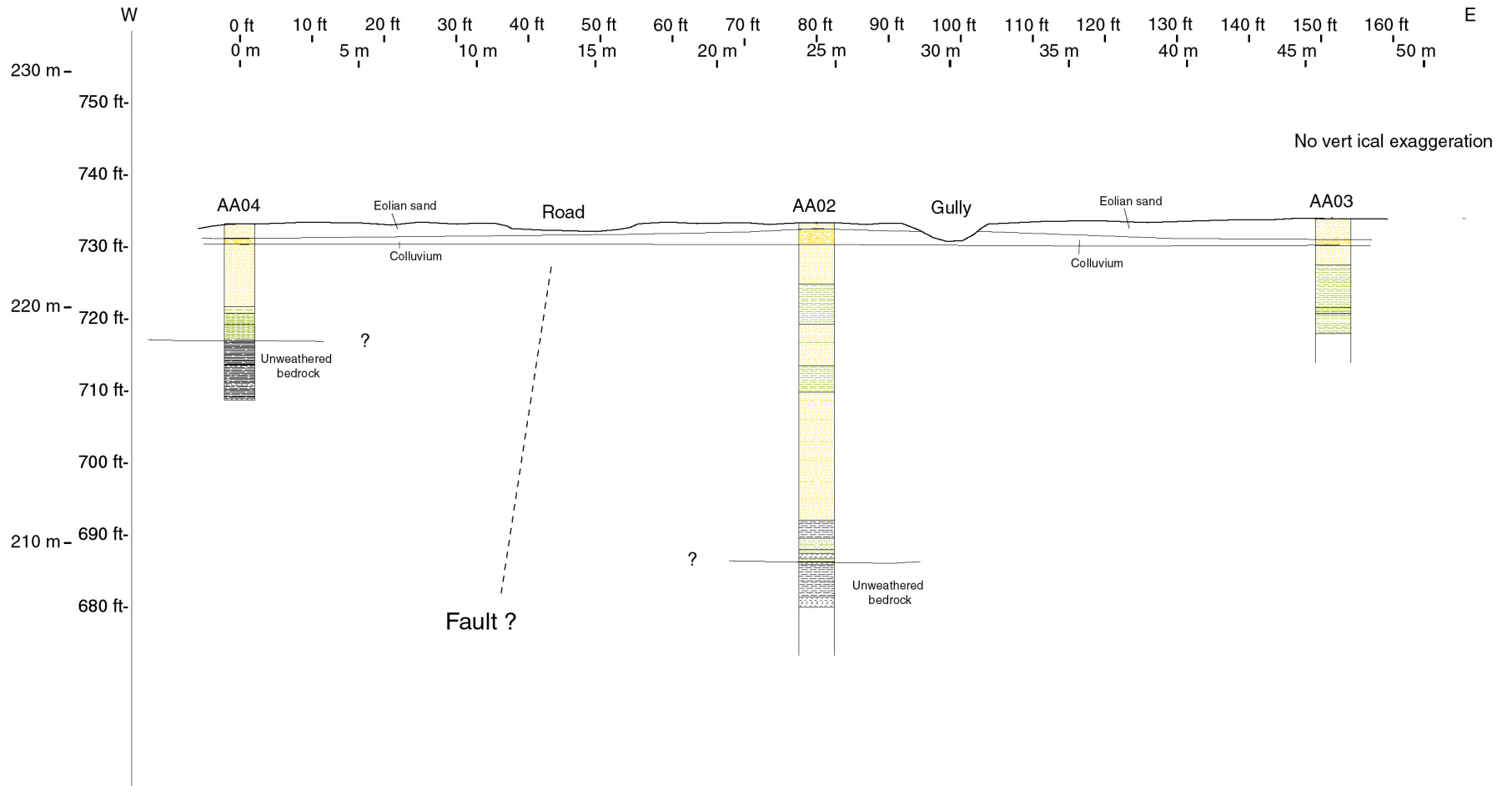


Figure 14- East-west cross section along the road showing thin surficial sediments and underlying bedrock. Note change in depth of weathering between hole AA04 and AA02. See Figure 12 for location of cross section.

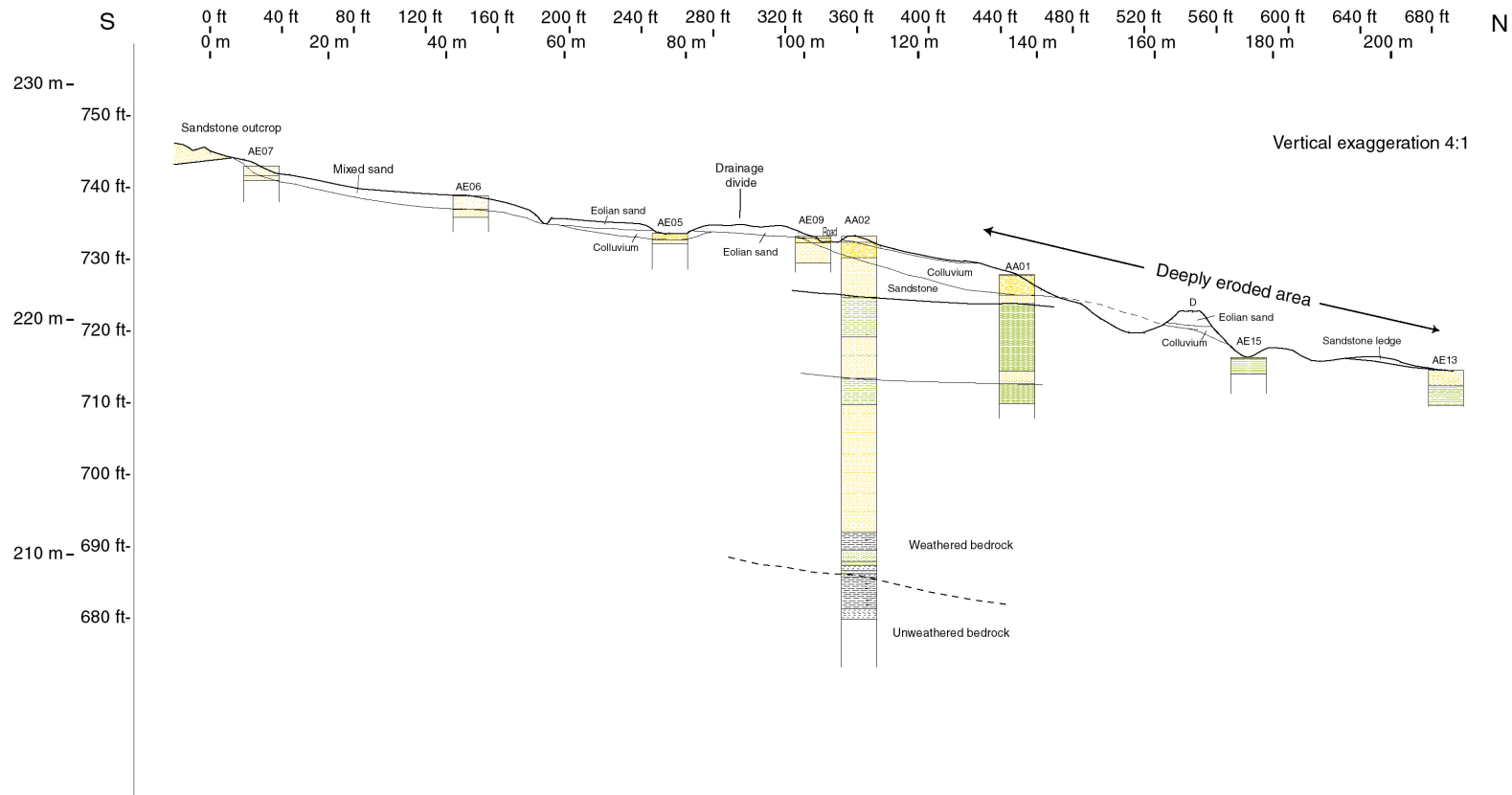


Figure 15- North-south cross section extending from the sandstone outcrop area north to a point close to the lake showing surficial sediments and underlying bedrock.  
See Figure 12 for location of cross section.

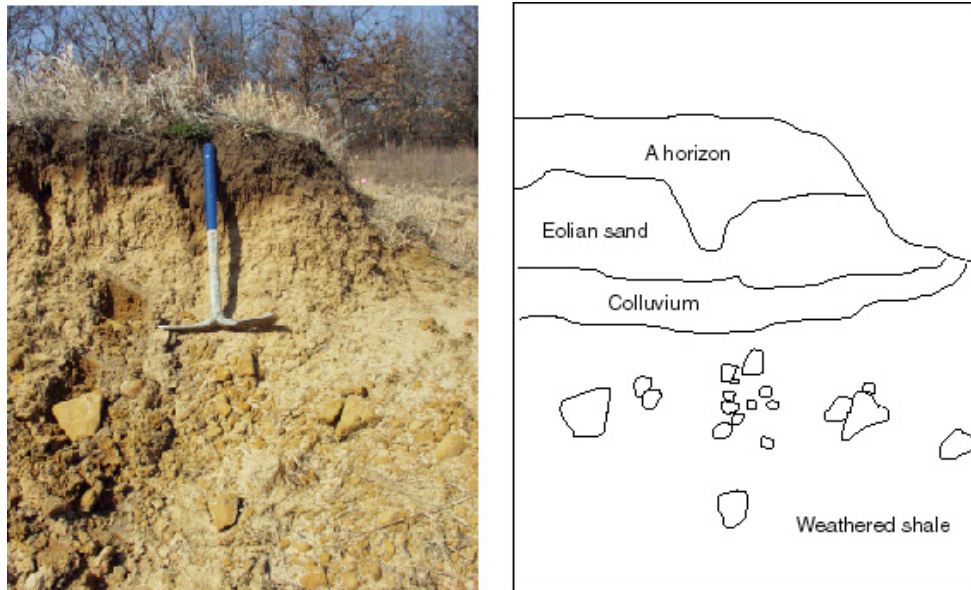


Figure 16- Stratigraphic section exposed in a soil pedestal within the deeply eroded area. The pick is 0.65m (2.15 ft) long. Sandstone clasts below the pick are eroded from the colluvial layer.



Figure 17- Aerial photo (1995) of the “B” research site (outlined in white) and adjacent areas.

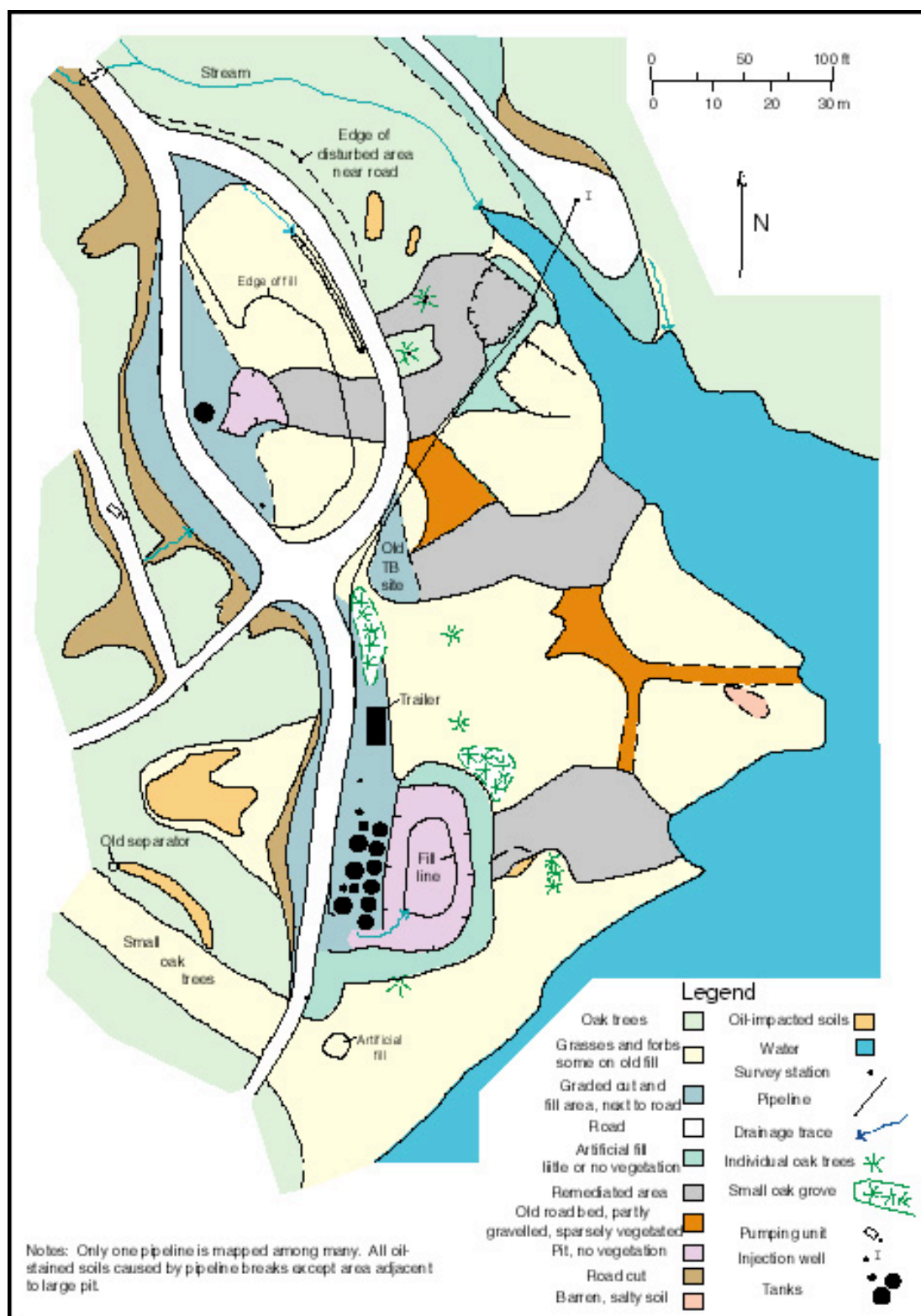


Figure 18- Features and vegetation map, "B" research site



Figure 19- Aerial view of the active tank battery, pit, salt scar, and Skiatook Lake. The lake level is above the normal pool elevation. Photo by Ken Jewell, U.S. Environmental Protection Agency, Ada, Oklahoma.

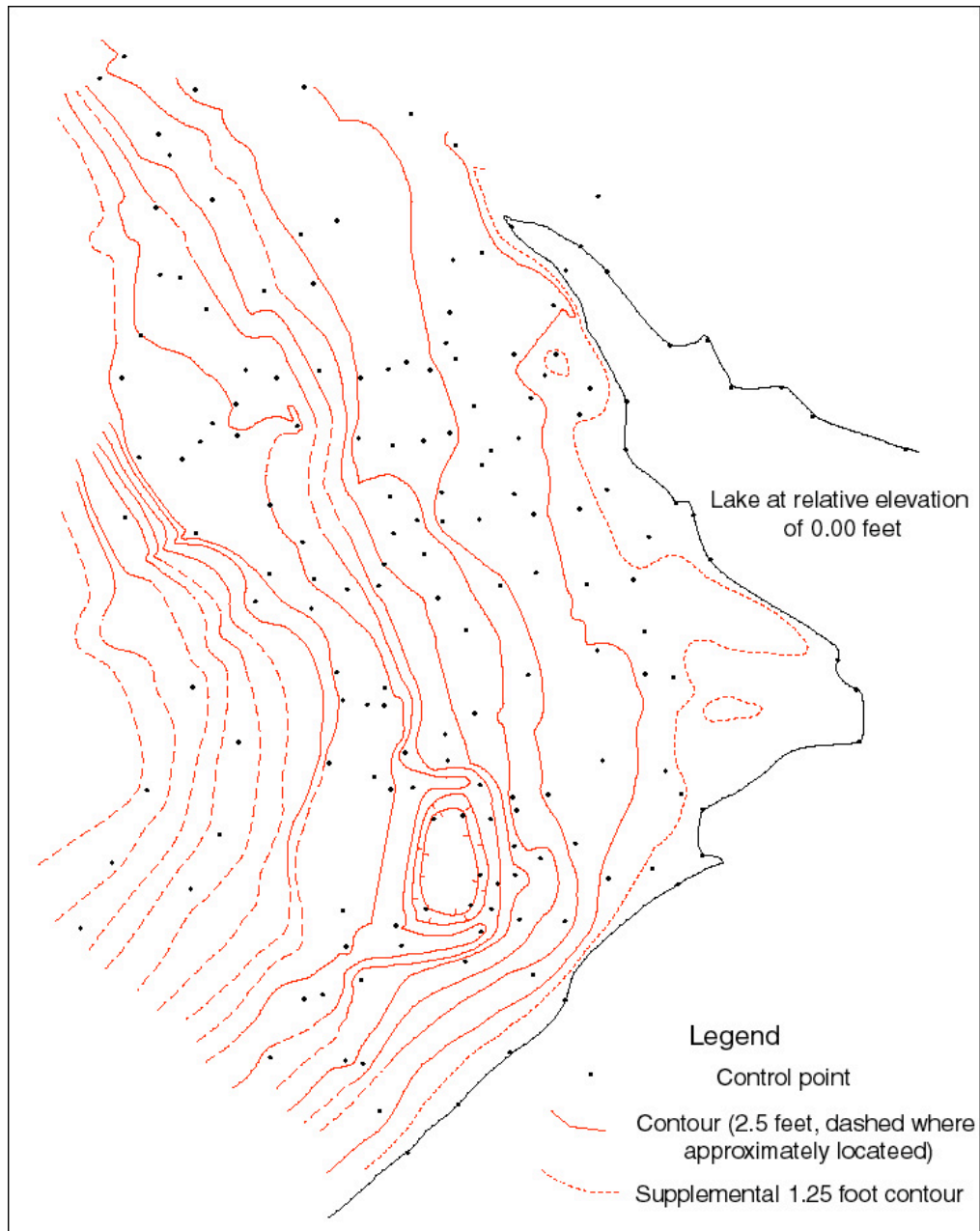


Figure 20- Topographic map of the "B" research site

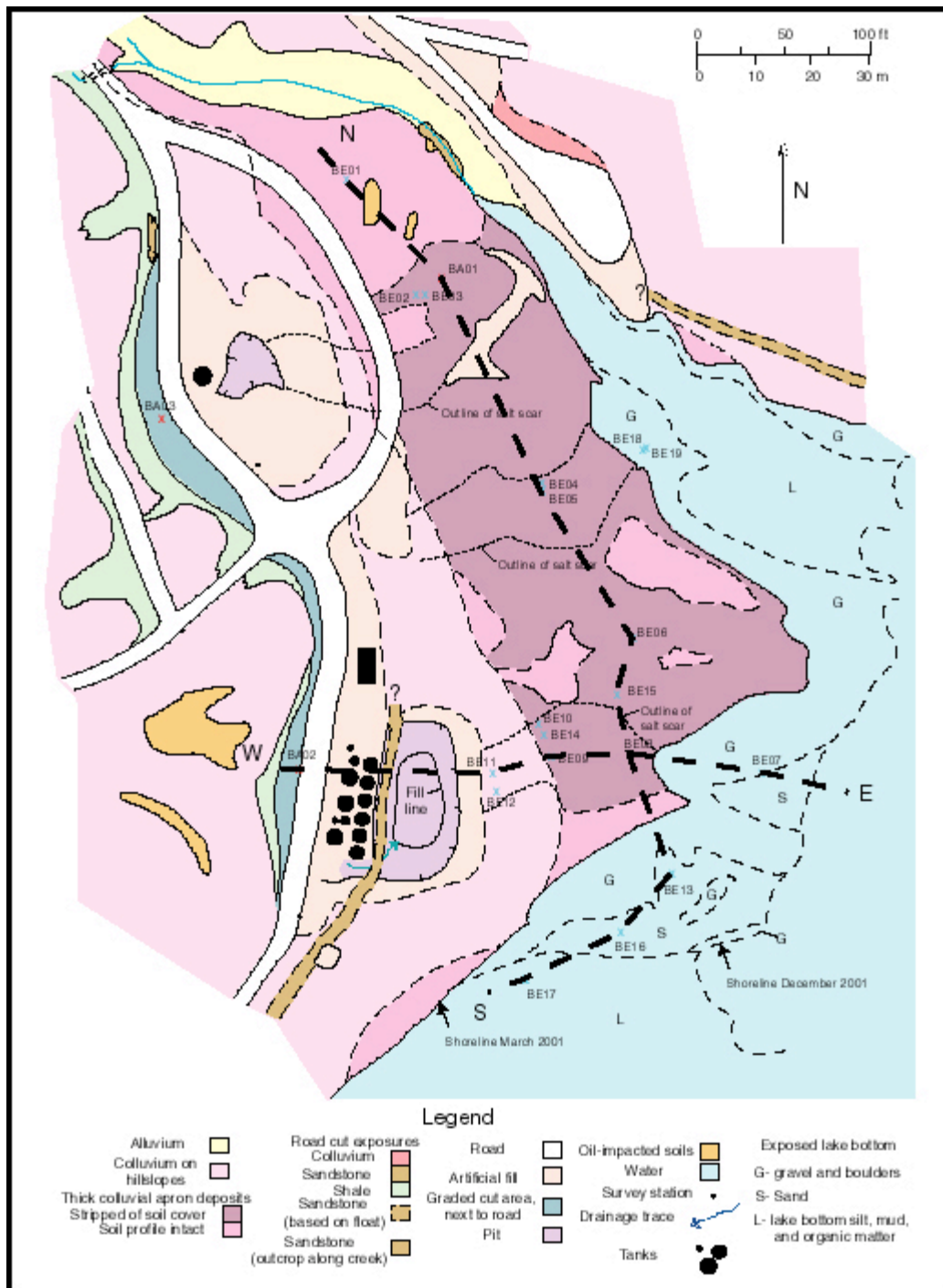


Figure 21- Geologic map of the “B” research site showing geology of the exposed lake bottom and locations of drillholes and cross sections.

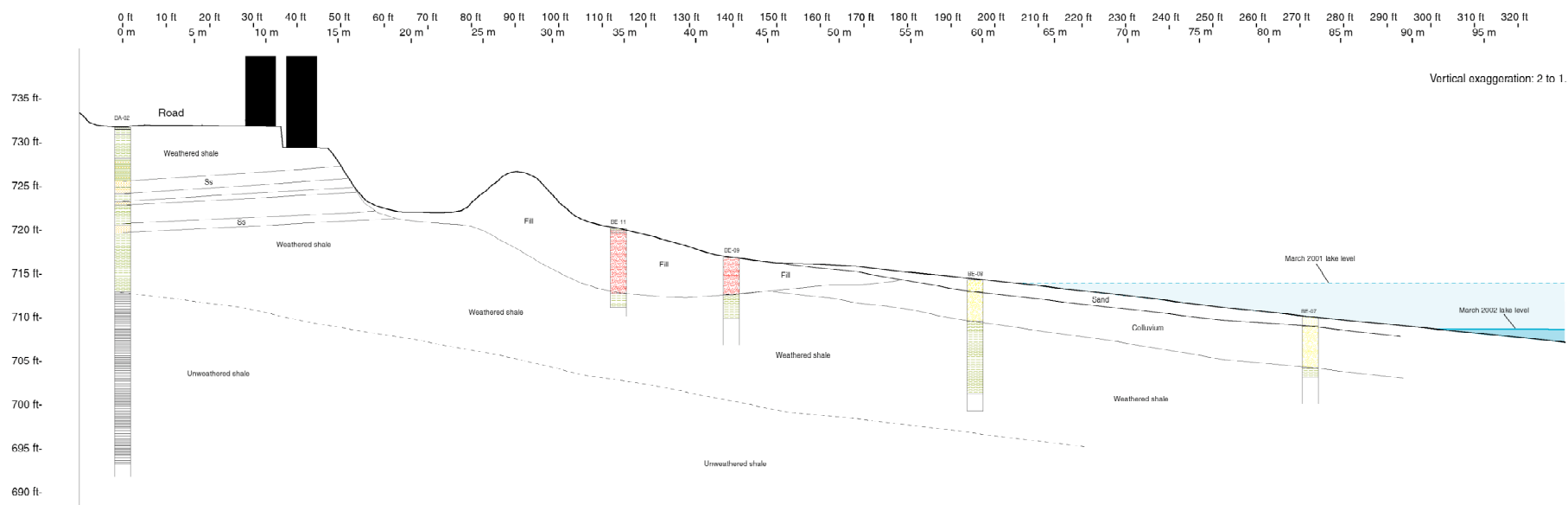


Figure 22- East-west cross section through the active tank battery down to the lake.  
See Figure 20 for location of cross section.

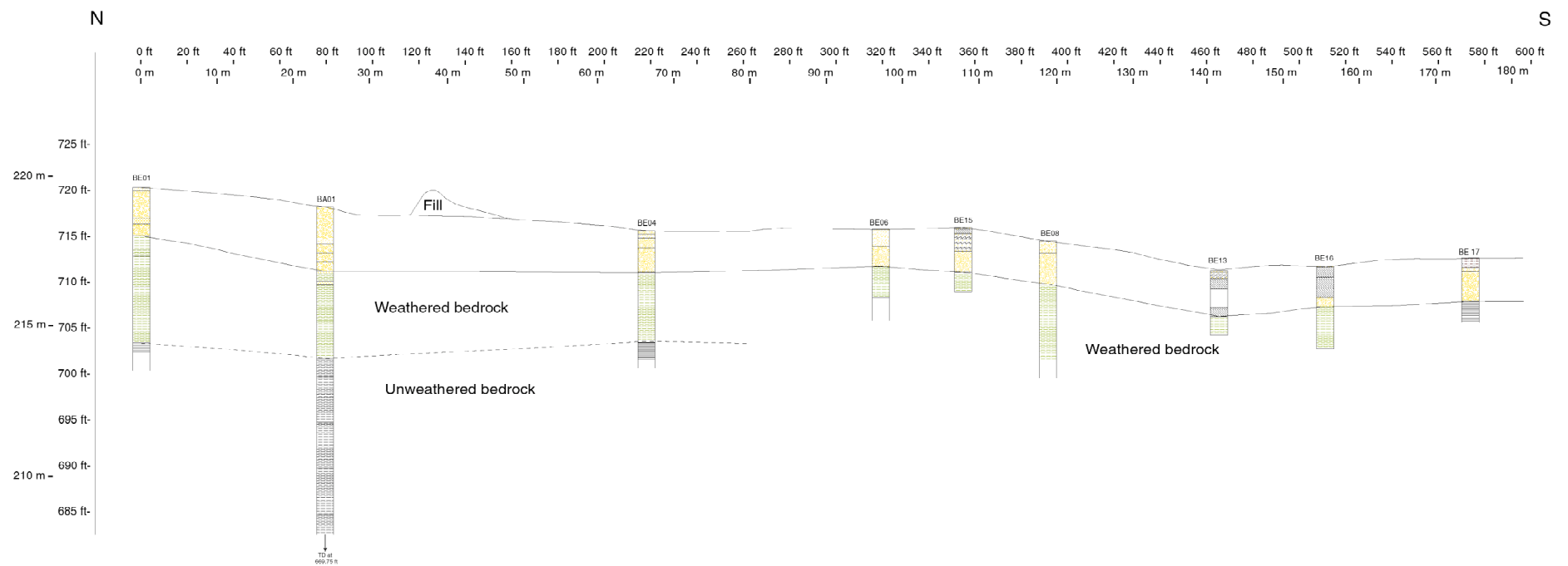


Figure 23- North-south cross section through surficial sediments underlying the terrace. See Figure 20 for location of cross section.